Thermal-mechanical Metal-forming Simulations in LS-DYNA Revisited

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Abstract:

In a former contribution (LS-DYNA Forum 2004) the properties of coupled thermal-mechanical simulations in LS-DYNA 970.5424 with reference to element free Galerkin (EFG) elements were assessed for a bulk metal forming test case. Some weaknesses were noted. This contribution revisits the problem and tests the progresses in LS-DYNA 971.7600 with regard to adaptivity in this kind of three-dimensional simulation. The results are compared to fully implicit solutions where possible. Additionally plastic heating of 3D-shells in a deep drawing benchmark example is assessed.
The paper highlights some of the difficulties encountered and the solutions found. Input decks may be downloaded from www.rudolf-boetticher.de.

Keywords:

Coupled simulation, adaptivity, EFG, implicit, LS-PrePost

1 Introduction

A coupled thermal-mechanical numerical analysis is necessary to simulate metal-forming processes such as rolling, extrusion or stamping. EFG (element free Galerkin) elements may be beneficial for the analysis. EFG does not introduce non-physical energy in the system to control hourglass modes, and promises more robustness and smoother results for the cost of longer computation times. Implicit simulations are also important in this context, because they do not need mass scaling as explicit forming simulations often use.
Two years ago a well-known bulk forming benchmark example was investigated and some weaknesses of LS-DYNA were noted [1]. This contribution revisits the problem and tests the progresses in LS-DYNA 971.7600 with regard to adaptivity, EFG elements, and implicit method in this kind of three-dimensional simulation.
The paper is organized as following. In section 2 the generic case of adaptive 3D solids is treated. In the next section the focus is on axisymmetric elements. Section 4 treats coupled simulations for 3D shells. Then some concluding remarks are given.

2 Plastic heating of 3D solids

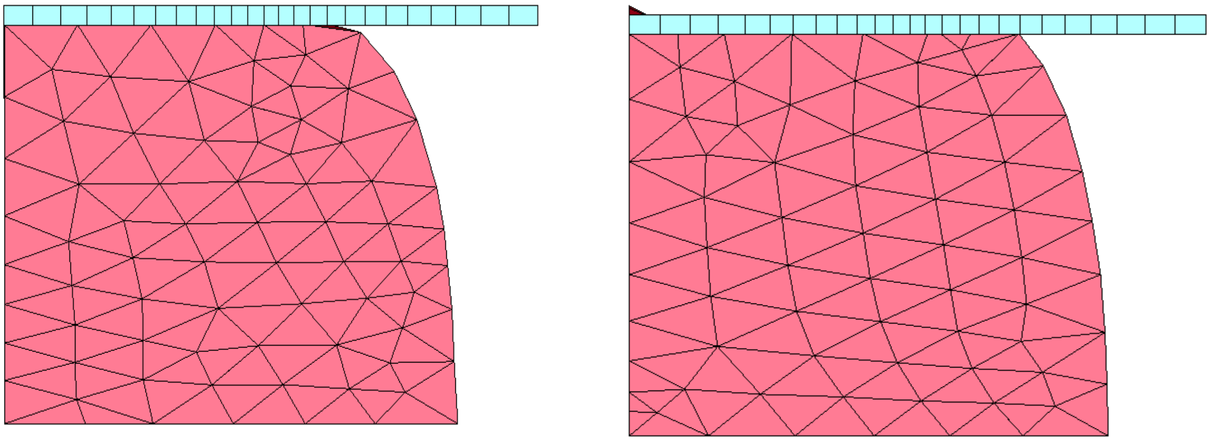

Figure 1: In the upsetting example may a high frequency of mesh adaption cause the stick condition at the stamp not to take effect (left compared to right). A high enough resolution of the rigid stamp is important.

Upsetting a cylindrical billet is a well-known benchmark example for nonlinear simulation programs. In the benchmark problem of Lugt and Hueting; treated here and in [1], a low carbon steel sample has an initial height of 36mm, radius of 9mm, and initial temperature of 20C. The total axial compression between two perfectly rough cylinders is 44% in 1.6s. There is no heat transfer to the environment (Figure 1). The variation of the stamp to a sinusoidal form may also be found in the literature (Figure 2).

2.1 Adaptive meshes

There is an r-adaptive remeshing feature in LS-DYNA for tetrahedrons (`ELFORM=13`), which is a one-pass adaption. It is invoked by setting `ADPOPT=7` on `*CONTROL_ADAPTIVE` (btw wrong echo of `ADPOPT` in LSPP/LS-PREPOST) and setting `ADPOPT=2` on the `*PART` card. The parameters `RMIN` and `RMAX` of the new mesh are given on `*CONTROL_REMESHING` (and not on `*CONTROL_ADAPTIVE`). The outer surface of the deformed part is calculated and remeshed. This yields a globally refined mesh of the part strongly dependent on the parameter `RMAX` rather than a graded mesh with local refinement in areas with high plastic strain or high stress gradients. Another restriction for the adaption is best explained with the original message from the messag file: “Nodes are shared by parts that are set for r-adaptive meshing and parts that are not. Mesh compatbility at these nodes will not be maintained after remeshing. These parts should be merged into a single part.” This implies that the resolution of the rigid stamp determines the resolution of the whole bulk. Therefore often a high count of redundant elements are generated and a work around is lacking (Figure 2 and 3).

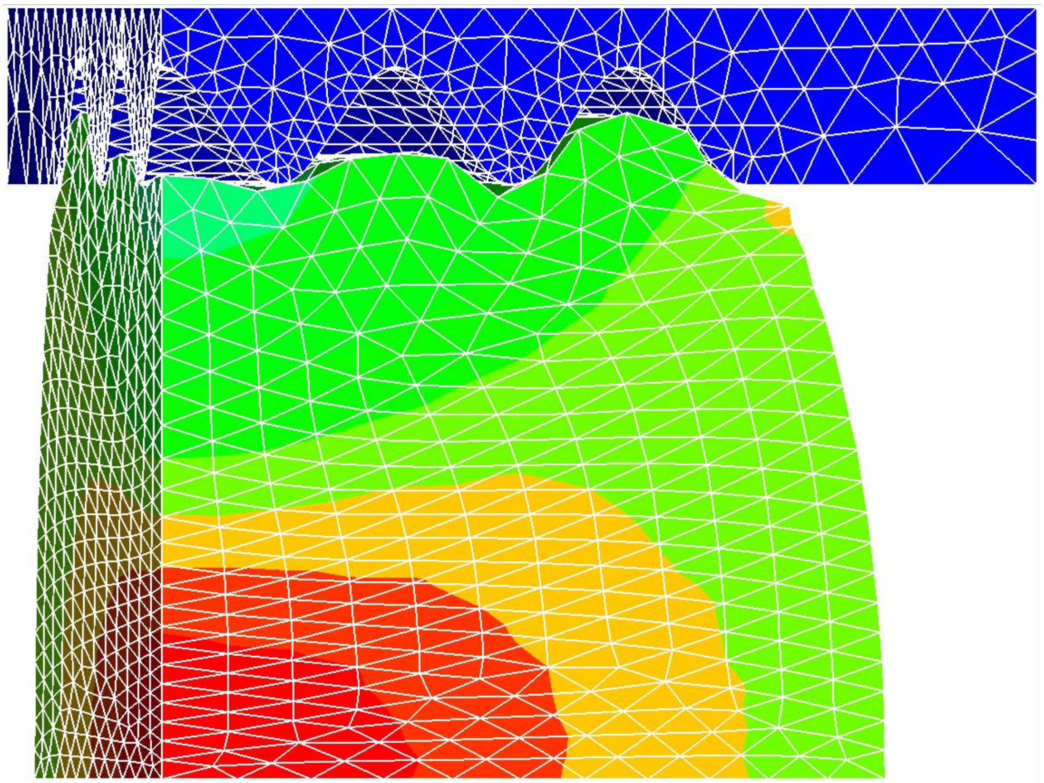

Figure 2: Temperature distribution with a sinusoidal rigid stamp and a billet of EFG tetrahedrons.

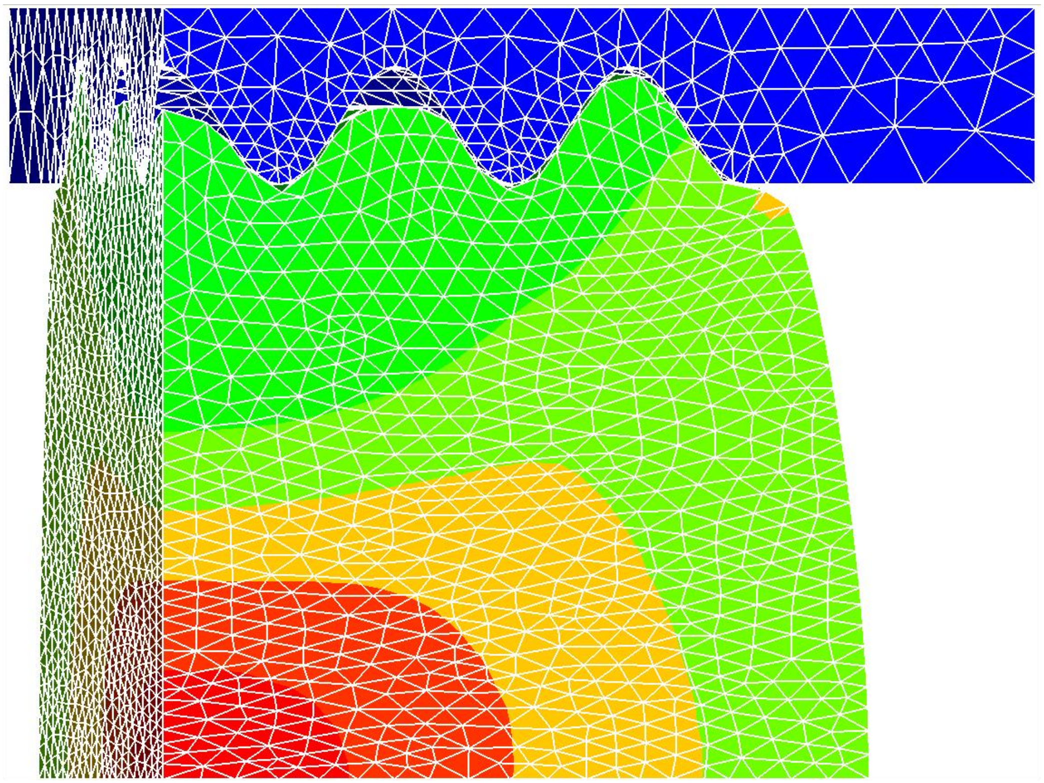

Figure 3: Temperature distribution with a sinusoidal rigid stamp and a billet of ELFORM=13 in an implicit adaptive simulation. The r-adaptive remeshing in LS-DYNA is based on the outer surface geometry and not on local refinement based on plastic strain or similar indicators. It yields more globally refined mesh rather than a pronounced grading of the mesh. The parameter `RMAX` on `*CONTROL_REMESHING` dominates the remeshing.

For the upsetting example mesh adaption makes it impossible to prescribe a stick condition at stamp by a `*BOUNDARY_PRESCRIBED_MOTION_SET` card like in the example of LSTC's thermal course [11], because the node numbers are changing. A contact interface is needed (Figure 1). The interference of two incremental algorithms, like the full remeshing during adaption and the penalty contact algorithm with friction here, may, however, cause undesirable results. A high mesh adaption frequency causes the stick condition (`FS=1.0`) at the tool not to take effect. This is similar to the effect at fluid structure interfaces, where material interface reconstruction, penalty contact algorithm and ALE advection may interfere detrimentally [2,3,4]. Setting the parameter `ADAPFREQ` on `*CONTROL_ADAPTIVE` to a high value is a quick alternative in order to switch to a non-adaptive run. As preliminary bottom line remains that remeshing should be utilized economically.

2.2 Contact, EFG and implicit

Though there is a great deal of information on contacts [9], I am often unsure whether these tips apply to various versions of LS-DYNA currently in use. I am confident that other users feel the same. Here a `*CONTACT_FORMING_SURFACE_TO_SURFACE` with `SLDTHK=0.01mm` and default penalties was used. The `ONE_WAY` option was not robust and I guess this is due to the varying mesh resolution of the billet during the adaptive process, which is a succession of restart jobs. Prescribing a damping by `VDC=200` was beneficial for avoidance of negative volume errors in beginning of these restart jobs for some explicit simulations.

Setting up an EFG analysis in LS-DYNA is easy as EFG is treated pretty much like another element form [1]. A *SECTION_SOLID is switched to *SECTION_SOLID_EFG with appropriate specifications on the third line (here: `1.4,1.4,1.4,,,4,3`) and that's it. EFG promises more robust and smoother results. Since `ELFORM=13` needs no hourglass control the property of EFG being a luxury hourglass control is not relevant here. The EFG tetrahedrons may be use with adaptivity and this works with the plane stamp of Figure 2. For the more demanding sinusoidal stamp the adaption step fails very often during the initialization of the EFG elements in the embedded restart run. The mass scaled EFG elements seem not to be especially good in tolerating penalty force peaks from the contact interface. The EFG simulation is not more robust with respect to program abortion than the standard elements. Do not expect decks that abort with standard elements to work with EFG elements.

It is easy to start an implicit run in LS-DYNA just by adding a couple of cards. Always try out the double precision version first in case of hard to explain errors. The implicit simulation does not necessitate mass scaling. Implicit works with adaptivity and solves the problem of Figure 3 well. Note the filling of the sinusoidal stamp as compared to the EFG analysis without remeshing. The implicit EFG solid element does not work with 971.7600. The run starts and soon stops with faulty results.

2.3 Coupled simulation

Coupled thermal-mechanical simulations work with remeshing. The plastic heating, the plastic deformation work converted into heat, raises the billet's temperature (Figure 2). The projections of thermal data are reasonable as far as the development of the isotherms in LSPP is concerned. Postprocessing with the `History` function and the `Tprint` file is hindered because the number of for instance the center node is changing during the remeshing cycles. Figures 4 and 6 show this effect. I guess that frequent adaption causes a loss of plastic heating directly after an adaption.

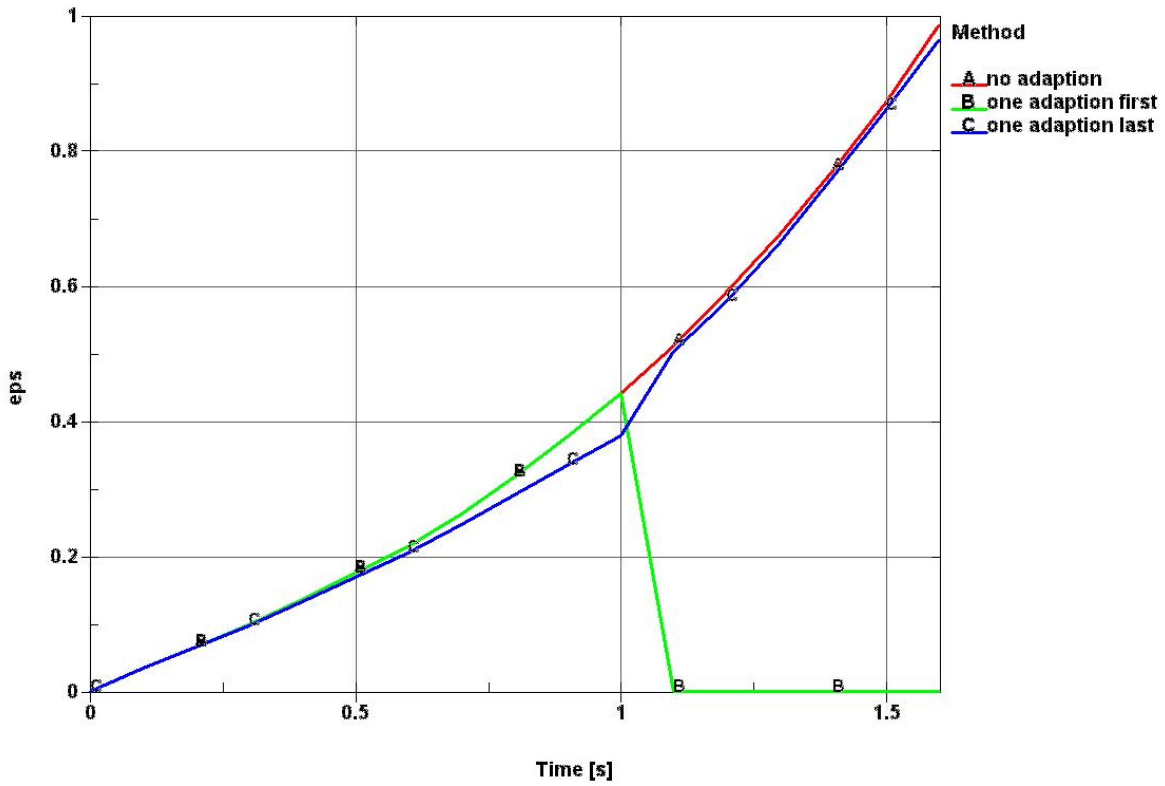

Figure 4: Effective plastic strain in the center in the 2D upsetting example for a simulation without and with one mesh adaption. B shows the curve for the node that is initially in the center and C shows it for the node that is there after adaption (and was somewhere else before). `*DATABASE_3DPLOT` *frequency was 0.1. The fact that after mesh adaption curve C touches curve A is evidence that the projection of the plastic strain is correct.*

3 Plastic heating of axisymmetric shells

It is not clear whether the demand for the axisymmetric 2D element is so considerable so that it is full-blown in LS-DYNA. The generic case seems to be the 3D case. The LSTC thermal guide treats an axisymmetric version of the upsetting problem [1] and therefore following findings should be documented.
The standard elements (`ELFORM=15`) work fine. Time step adaptivity in the thermal solver, which is always implicit in LS-DYNA, works fine as well. The robustness may be slightly enhanced by using only one integration point (`GPT=1` on `*CONTROL_THERMAL_SOLVER`). Ii is impossible to exempt a rigid part from thermal processing. The contact card must be changed to `*CONTACT_2D_AUTOMATIC_SURFACE_TO_SURFACE_THERMAL` with thermal parameters on the third row.
Time step adaptive implicit simulation of the mechanical part works well. Reduction of element count during adaption yields an unconstrained nodes error message. While it is easy to insert the one or two cards in order to trigger an implicit solution in LS-DYNA, one gets often stuck in situations where a more intuitive definition of (SPC) boundary conditions and forcing functions that is robust under switching between implicit, explicit and adaptive is lacking. Prescribing constraints on `*MAT_RIGID` rather than somewhere else is imperative.

Explicit and implicit mesh adaptive coupled simulations seem to work fairly on first sight. LSPP plots with `History->Element->Effective Plastic Strain/Temperature` or `ASCII->Tprint->Temperature` deliver misleading results, because element and node numbers may be assigned to new geometrical positions during the remeshing. While the bookkeeping for the mechanical properties like the plastic strain seems to work fairly (Figure 4) the projection of plastic heating during mesh adaption definitely yields too high a temperature. This is displayed in Figure 6 where the center node temperature is shown in the upsetting example. No and one remeshing was used. Shown are the history plots for no adaption, for the center node selected in the initial configuration and the final configuration. The temperature spike after mesh adaption is eye-catching.

A still ongoing nuisance with the mid August edition of LSPP on Windows is saving of plots in a graphic format like *.gif for hardcopy documentation. LSPP behaves pretty differently on different boards, graphic adapters and XPs. A workaround for non xy-plots is to paste `full; print jpg` … in the command box down at the left from the command log down at the right to achieve the resolution of the full screen. The font is still horrible. The reader may forgive the quality of the graphics and is referred to the CD-proceedings or [8] for a more comprehensive documentation in color.

An axisymmetric EFG element exists in 971.7600 (`ELFORM=44`). It does not work implicitly. It works however in coupled explicit simulations. The element, however, behaves less robust regarding its forcing by the rigid stamp (Figure 5). Reducing the mass scaling by factor 10, which is not practical at all, may alter this behavior slightly. A mesh adaptive explicit simulation with EFG elements is possible in the SMP 971.7600 version bundled with ANSYS. However, the results are not good. The axisymmetric EFG elements are not yet full-blown.

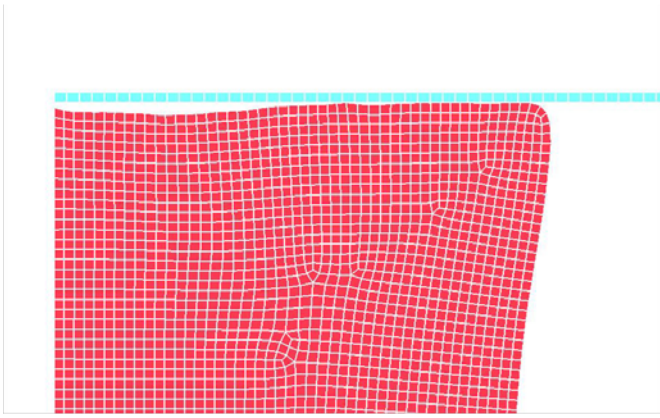

Figure 5: Error situation with mass-scaled axisymmetric EFG elements near the interface. Standard elements work without ado.

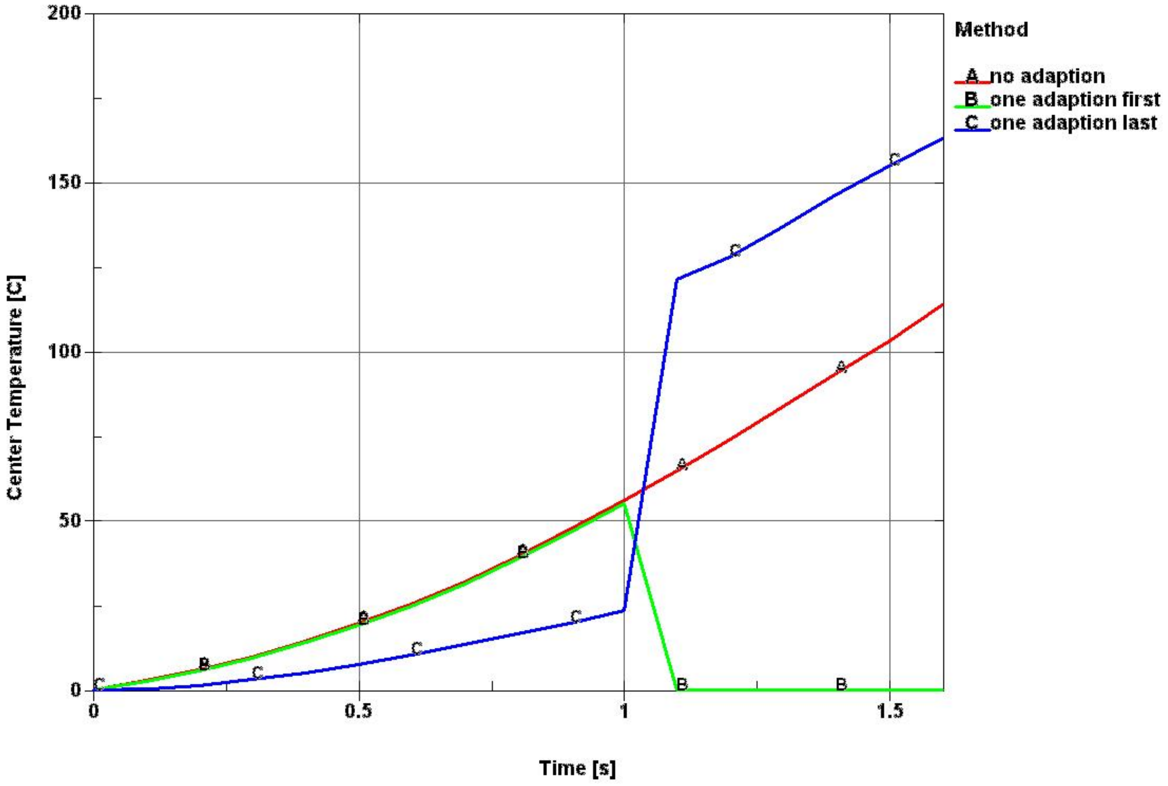

Figure 6: Center temperature in the 2D upsetting example for a simulation without and with one mesh adaption. B shows the curve for the node that is initially in the center and C shows it for the node, which is there after adaption (and was somewhere else before). `*DATABASE_3DPLOT` was set to 0.1. Clearly the faulty projection of temperatures at the time of the mesh adaption may be spotted.

4 Plastic heating of 3D-shells

Considerable progress has been made since the inspection of coupled simulation for 3D-shell in the supplementary material of [1,8]. Nearly full functionality is available now. In order to demonstrate this a prototype hemispherical deep drawing example (Figure 7) is utilized.

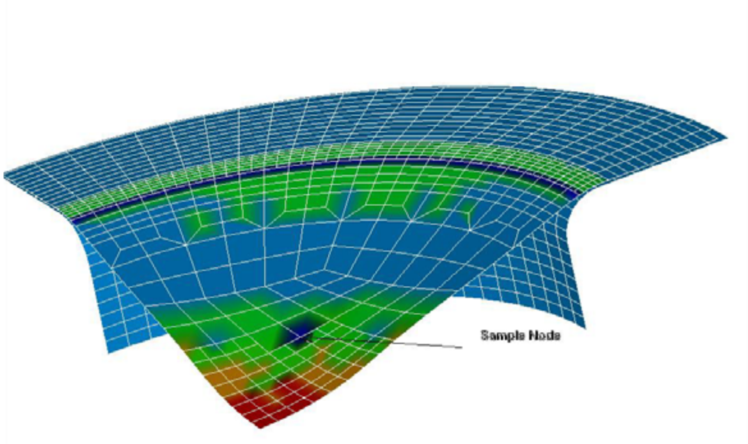

Figure 7: Temperature distribution for the prototype hemispherical deep drawing example adapted from [6,7].

The constrained base h-adaptive method for 3D-shells is local in contrast to the r-adaptive remeshing of solids and axisymmetric elements. It is normally based on geometrical features of the deformed shells. The undocumented `ADOPT=4` uses an error indicator. The EFG 3D-shell (`ELFORM=41`) works for explicit coupled simulation. Mesh adaption is allowed in some 971.7600 versions like the SMP version bundled with ANSYS. In other versions a `*CONTROL_ADAPTIVE` card is not tolerated in the deck. This shows the perpetual beta character of LS-DYNA. An implicit EFG 3D-shell is not yet implemented. A quick inspection of the development of plastic strain near the location of the maximum for an adaptive simulation with standard elements and a non-adaptive simulation with EFG element shows that the EFG elements do not substitute mesh adaption.

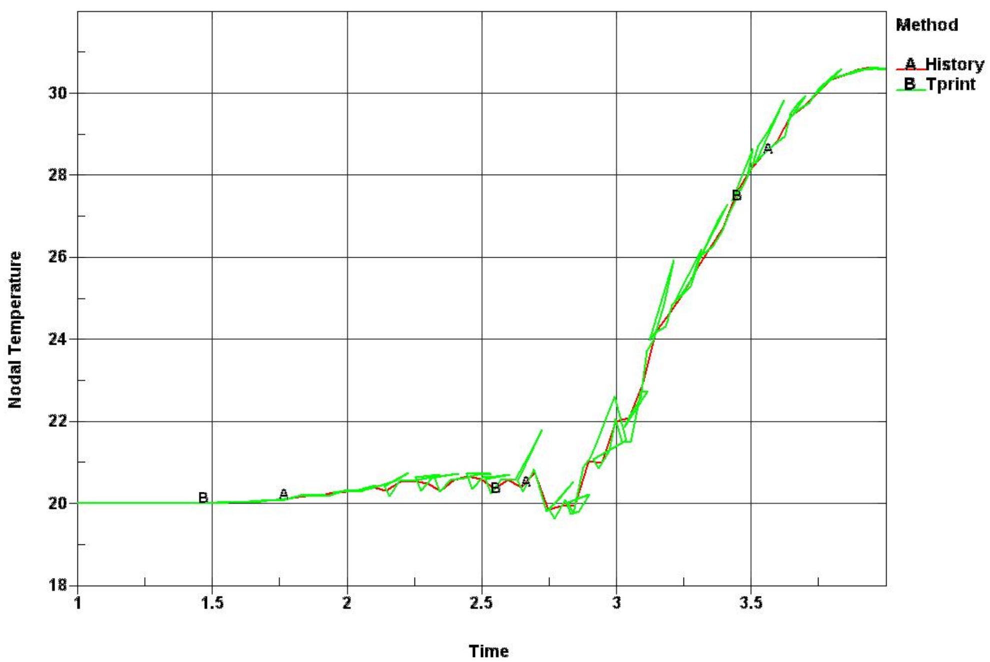

Figure 8: Temperature at the sample node marked in Figure 7 as reported from the `Tprint` file and with `History->Nodal` function in LSPP. The data from `Tprint` file show the two pass adaptivity. This effect appears more clear-cut, if adaptive thermal time stepping is used. The thermal calculation is repeated for the r-adapted shell mesh for the last adaption interval. At the moment there is no two-pass adaptivity for implicit mechanical simulations implemented. The functionality and the criteria used for adaptive time stepping on `*CONTROL_THERMAL_TIMESTEP` should be enhanced.

Standard elements also work implicitly. Implicit only works with one pass adaptivity. For implicit calculations with the SMP version always consider to try out the double precision version first in case of errors. As the thermal simulation is always implicit this claim refers to any coupled simulation. This helped in an error situation encountered with 3D-shells while preparing this paper. Otherwise in my opinion not all single precision implicit calculations with the SMP version deliver wrong results.
Figure 8 depicts the course of the temperature at a sample node. Figure 7 displays the temperature distribution on the adapted mesh near 2.6 s. The constrained based h-adaptive method generates a slight temperature loss at the time of adaption. This effect used to be more pronounced in former versions.

5 Conclusions

The features for coupled thermal-mechanical simulations have advanced in LS-DYNA since 2004, however, are yet not full-blown. Some decks may or may not work for different versions of 971.7600.
For 3D solids mesh adaptive thermal-mechanical simulations work explicitly and implicitly. The projection of thermal data during the remeshing step is correct. Tetrahedrons may be interchanged with EFG elements for adaptive explicit simulations. The mesh adaption is more global than local and yields less graded meshes that one may expect. The interference of mesh adaption and contact penalties may severely change the friction behavior at the contact surface.
For axisymmetric shell elements thermal-mechanical simulations work explicitly and implicitly with standard elements. Mesh adaption works for the mechanical but not for the coupled simulation, because the projection of thermal data after remeshing is faulty. The axisymmetric EFG element works explicitly, however its deformation pattern is less robust to mass scaling than the standard elements. Implicit axisymmetric EFG is not implemented in 971.7600. Mesh adaption and contact surface may interfere detrimental. A better concept for the `History` function in LSPP for adaption by remeshing is required.
The coupled simulation for 3D-shells has now nearly full functionality and the projections during adaption are fair. Only an implicit EFG 3D-shell and a two-pass adaptive implicit method are lacking.
During the progress of the work several malfunctions of the programs and inconsistencies of the documentation were found. They were reported and documented in the LS-DYNA group [5], which has a vivid messaging. Downloads of input decks are available at [8].

6 References

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